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INVESTIGATION OF THE RECIRCULATION REGION OF A FLOW FIELD CAUSED BY A JET IN GROUND EFFECT WITH CROSSFLOW

T. W. Binion, Jr.
ARO, Inc.

September 1970

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FOREWORD

The test reported herein was sponsored by the Air Force Flight Dynamics Laboratory (AFFDL), Air Force Systems Command (AFSC), under Program Element 62201F, Project 8219.

Results of the test were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract F40600-71-C-0002. The test was conducted from March 19 to April 30, 1970 under ARO Project No. PD0084, and the manuscript was submitted for publication on June 30, 1970.

This technical report has been reviewed and is approved.

George F. Garey
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ABSTRACT

A wind tunnel investigation was conducted in the Low Speed Wind Tunnel (V/STOL) to determine the velocities in the recirculation region of the flow field produced by the interaction of a jet impinging on a ground plane with crossflow. Axial and vertical velocity component measurements were obtained with a forward-scattering laser Doppler velocimeter. Test results provide two-component velocity fields and indicate that the jet-to-free-stream velocity ratio is much more important in determining the flow field than the magnitude of the individual velocities.

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I. ILLUSTRATIONS

NOMENCLATURE

D	Nozzle exit diameter, 1.06 in.
e	Base of natural logarithm
h	Height of nozzle exit above ground plane, in.
p	Pressure, psfa
p_t	Total pressure, psfa
q	Dynamic pressure, psf
U	Axial velocity component, ft/sec
V	Vector sum of U and w, ft/sec
V_R	Ratio of jet exit to free-stream velocities
w	Vertical velocity component
x	Axial distance from nozzle centerline, positive downstream, see Fig. 2
y	Transverse distance from nozzle centerline, see Fig. 2
z	Vertical distance from ground plane, see Fig. 2

SUBSCRIPTS

j	Jet exit condition
∞	Free-stream conditions

SECTION I
INTRODUCTION

A VTOL aircraft hovering in ground effect may be subjected to lift loss and instability caused by the interaction of the lifting and crosswind streams. It is well known from VTOL experience that a vertical recirculating flow field is established on the windward side of a hovering vehicle. Colin and Olivari (Ref. 1) have demonstrated the basic characteristics of the flow field using flow visualization methods. The flow field can be divided into regions consisting of the free-jet, impingement, wall-jet, recirculation, and free-stream regions as shown in Fig. 1 (Appendix I).

It is the purpose of the investigation reported herein to measure the local velocity vectors in the recirculation region to gain further insight into the flow mechanism. The experimental investigation was conducted on a jet impinging on a ground plane with crossflow for the Air Force Flight Dynamics Laboratory (AFFDL/FDCC) in the Low Speed Wind Tunnel (V/STOL) of the Propulsion Wind Tunnel Facility (PWT).

The tests were conducted with the jet exit one and four diameters above the ground plane at three jet-to-free-stream velocity ratios and three values of the jet dynamic pressure. Two-component velocity measurements were obtained with a forward-scattering laser Doppler velocimeter.

SECTION II
APPARATUS

2.1 TEST FACILITY

The Low Speed Wind Tunnel (V/STOL) is a continuous-flow, closed-circuit, constant-total-pressure wind tunnel in which velocities from 5 to 250 ft/sec can be attained. Flow is generated by a single-stage, fixed-pitch fan driven by a 100-hp electric motor through a variable-speed magnetic clutch. Speeds below 20 ft/sec are attained through the use of the throttle described in Ref. 2.

The test section has a 30- by 45-in. rectangular cross section and is 72 in. long. The horizontal test section walls each contain ten slots which provide an overall test section wall porosity of 2.4 percent. The

solid vertical walls are made of plexiglass. The tunnel was equipped with a ground plane 37 in. wide by 56 in. long and located 7 in. above the bottom wall.

2.2 TEST ARTICLE

The test article consisted of a convergent nozzle oriented normal to the ground plane as shown in Fig. 2. The test installation is shown in Fig. 3. The nozzle was constructed from a standard 3- to 1-in.-diam, schedule 40 concentric pipe reducer. The nozzle exit pressure distribution is presented in Fig. 4. A 3/8-in.-diam tube was fixed to the upstream side of the nozzle to provide smoke particles for scattering the laser light. The smoke tube was positioned so that smoke particles were entrained into the jet boundary and thus distributed throughout the flow field.

2.3 INSTRUMENTATION

Axial and vertical velocity components were measured with a forward-scattering laser Doppler velocimeter. The velocimeter indicated in Fig. 2 consists of a helium-neon laser, an optics package, focusing lens, phototubes, and associated electronics. The optics package split the laser beam into three parts: an illuminating, a horizontal reference, and a vertical reference beam. The three beams, which in cross section are at the vertices of a 45-deg right triangle, are converged to a common intersection region by the lens. Since the focusing beams form the edges of a triangular pyramid, it is impossible to position the focal region on the surface of the ground plane without one of the beams striking the plate. Thus, there is a minimum distance below which data cannot be recorded. The minimum distance, which is a function of the lens focal length, beam separation, and ground plane width, was 0.295 nozzle exit diameters.

Photons striking particles within the flow field radiate in spherical wave fronts from the particles at frequencies which have been shifted by the Doppler effect. Only those photons which strike particles within the focal volume formed by the intersection of the illuminating and reference beams are precisely aligned with the reference beam and contribute to the velocity measurement. The phototubes are aligned with the reference beams and produce an electronic signal whose frequency is directly proportional to the velocity of the scattering particle. The electronic signal from the phototube is processed by a spectrum analyzer. The measured velocity component is in a plane formed by the

illuminating and reference beams and is perpendicular to their angular bisector. The data represent the most probable velocity within the focal volume. The focal volume is defined in Ref. 3 as the $1/e^2$-intensity contours at the illuminating and reference beam intersection. The installation resulted in an ellipsoidal focal volume with major and minor diameters of 2.02 and 0.022 in., respectively. A more complete description of the laser velocimeter and its operating characteristics may be found in Refs. 3 and 4. The velocimeter was mounted on a three-degree-of-freedom traverse system whose travel allowed the focal volume to be placed at any position in one quadrant of the flow field.

A row of pressure orifices was placed along the centerline of the ground plane to determine the location of the jet stagnation point. Pressure measurements were obtained with precision pressure balance transducers with full-scale ranges of 180 and 720 psf. The test section dynamic pressure was measured with a variable capacitance transducer with five selectable full-scale ranges varying from 0.028 to 28 psf.

2.4 PRECISION OF MEASUREMENT

The data contained in the report were determined from single-sample measurements. The uncertainties for the data are estimated from instrument precision and calibration curve-fit deviations. All uncertainties except for those associated with the laser velocimeter are based on a 95-percent confidence level. Because of inherent imperfections within the resonator cavity of the laser, the ideally coherent laser light contains extraneous radiation which varies randomly with time. The frequency of the extraneous radiation was in many cases very near the Doppler-shifted frequency produced by the flow field. In addition, the amplitude of the extraneous signals was equal to and sometimes greater than the data signal. Despite procedural efforts to discriminate between the data and extraneous information, it is felt that in some instances inappropriate measurements were recorded. Therefore, the confidence level of the velocimeter data is 85 percent.

The precision of the measurements reported herein is as follows:

V_∞	V_j	q_j	U	w	x, y, z
±0.5 fps	2 fps	±0.7 psf	±0.5 fps	±0.5 fps	±0.1 in.

SECTION III
PROCEDURE

Test conditions were established by maintaining a desired jet dynamic pressure and adjusting the tunnel speed to obtain the desired jet-to-free-stream velocity ratio. Tunnel speed was adjusted to compensate for changes in jet and tunnel temperature when either varied more than 10°F. Temperature variations during the testing period were generally under 20°F.

Vaporized mineral oil was introduced into the jet-free-stream interface to provide scattering particles for the velocimeter from a smoke generator outside the test section at a rate of about one ounce per hour. The oil condensate had to be removed from the tunnel walls and velocimeter optics twice daily to prevent unacceptable signal attenuation.

The center of the velocimeter focal volume was positioned at discrete points in the flow field with a three-degree-of-freedom traverse. Two-component velocity profiles were obtained in the z-direction holding the x and y positions constant. The velocity data were acquired by visually comparing an oscilloscope display of the phototube output with a superimposed signal from a high-frequency oscillator. Both signals were processed by the same spectrum analyzer through a switching arrangement prior to display on the oscilloscope. The frequency of the oscillator was adjusted until its oscilloscope trace coincided with the Doppler-shifted frequency trace from the velocimeter. The oscillator frequency, which is then directly proportional to the velocity, was recorded with an automatic data acquisition system.

At the end of the test program a tuft grid was installed in the test section. Tuft photographs were obtained to assist in interpretation of the velocity data. A summary of the test conditions is presented in Table I, Appendix II.

SECTION IV
RESULTS AND DISCUSSION

4.1 IMPINGEMENT REGION PRESSURE DISTRIBUTION

The centerline impingement region pressure distributions (Fig. 5) are presented in terms of the square root of the pressure coefficient

whose maximum value corresponds to the jet-to-free-stream velocity ratio. Calculation of the jet centerline locations from the empirical equation of Ref. 5 shows that for the test conditions at h/D = 1 the jet stagnation point should be within a few thousandths of an inch of the nozzle center. The ground plane pressure distribution for h/D = 1, shown in Fig. 5a, indicates that the jet stagnation point was upstream of the nozzle centerline: 0.1 diameter at V_R = 16.7 to 0.25 diameter at V_R = 6.3. However, at h/D = 4 the empirical equation gives jet centerline locations of 0.40 and 0.11 diameter for velocity ratios of 6.3 and 12.2, respectively, which agree very well with the data in Fig. 5b. Considering the flat pressure profile at the nozzle exit; it is difficult to visualize a flow condition which would cause the jet stagnation point to move upstream. Thus, one is led to the conclusion that the nozzle was misaligned at h/D = 1. Consequently, the location of the velocity data obtained at h/D = 1 should be shifted an amount corresponding to the displacement of the stagnation point.

4.2 RECIRCULATION REGION VELOCITY DISTRIBUTION

The axial and vertical velocity data are presented as the vector sum of the two components at a spatial location. The coordinate system, shown in Fig. 2, originates at the intersection of the nozzle centerline and the ground plane. The magnitude of all velocity data has been nondimensionalized by dividing by the free-stream velocity. The location of the tail of the vector corresponds to the spatial position of the data. The laser velocimeter provides information which is proportional to the magnitude of the velocity component, but it does not indicate the sign of the component. Therefore, the direction of each vector was inferred from photographs of a tuft grid placed in the flow field. Occasionally, it is apparent that one component of the data was in error. In these cases, an assumed value of the vector compatible with the neighboring data is indicated by dashed lines.

The velocity field obtained at a jet-to-free-stream velocity ratio of 16.7 is presented in Fig. 6. The recirculation region is clearly evident in the plane y = 0. Except for a small region near coordinate (5.5, 0.5) the magnitude of the vectors is less than twice the free-stream velocity. The large vertical velocity components at the wall-jet, recirculation-region interface (x/D = 1.5 to 5) were unexpected. The strong downflow does not appear to be compatible with a mixing layer model one would postulate for the interface. In the planes y/D = 4 and 8 the recirculation region is seen to move downstream as would be expected.

Data obtained at three values of the jet dynamic pressure at constant nozzle height and velocity ratio are shown in Fig. 7. The three superimposed flow fields correlate very well in the far field region. However, in the neighborhood of the wall jet the agreement is not as good. Some of the differences, particularly at a q_j of 10 psf, may be attributed to the extraneous radiation in the velocimeter signal discussed in Section 2.4. It should also be noted that the flow field, particularly at the wall-jet, recirculation-region interface, is highly turbulent. Turbulence appears on the velocimeter oscilloscope as a broad frequency band with reduced signal amplitude, which makes the assignment of an average value to the velocities more nebulous. The problem may be reduced somewhat by increasing the general level of the velocity magnitude, i. e., testing at higher values of q_j for a given velocity ratio. Nevertheless, the data indicate that the free-stream velocity is a suitable normalizing parameter and that the jet-to-free-stream velocity ratio is much more important in determining the velocity field than the level of the individual velocities.

The flow visualization data of Ref. 1 indicated a flow field with the presence of a vortex-like center in the recirculation region. Examination of the velocity fields shown in Figs. 6 and 7 indicates the presence of an apparent recirculation center. However, while a different observer may construct a different flow field in each case, the magnitude and possible directions of the vectors do not clearly indicate the presence of a vortex.

The position of the apparent recirculation center and the location of the free-stream separation point in the plane of symmetry are shown in Figs. 8 and 9, respectively, as a function of velocity ratio. For a constant velocity ratio, the data show a forward displacement of each event as nozzle height is decreased, as would be expected. The strength of the wall jet increases slightly as the height is lowered from 4 to 1 diameter, thereby requiring a longer distance for viscous dissipation to reduce the energy of the wall jet to that of the free stream. The location of the recirculation center and separation point is considerably different from that reported in Ref. 1. It is felt that the reasons for the discrepancy at the present stage of understanding of the flow mechanism and data acquisition technique would be too speculative to be useful. It should be noted that, although a more detailed (finer spatial increment) investigation may alter the inferred velocity field somewhat, the alteration would not be sufficient to bring the two sets of data into agreement.

SECTION V
CONCLUSIONS

The investigation of the velocity field produced by the interaction of a jet impinging on a ground plane and a crossflowing stream resulted in the following conclusions:

1. The location of the apparent recirculation center and the free-stream separation point are weak functions of nozzle height up to an h/D of 4.

2. The ratio of jet-to-free-stream velocity is a much more important parameter in determining the flow field than the magnitude of the individual velocities.

3. Free-stream velocity is a suitable normalizing parameter for the velocity data.

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APPENDIXES

I. ILLUSTRATIONS
II. TABLE

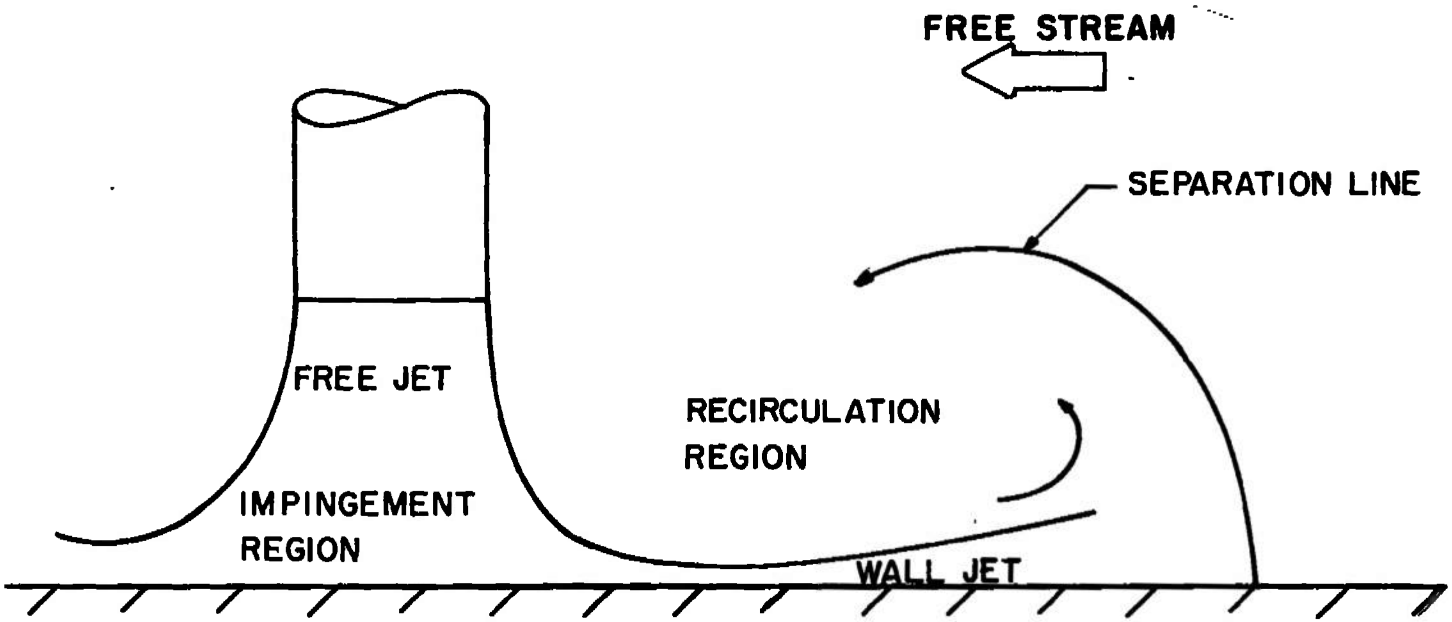


Fig. 1 Flow-Field Characteristics

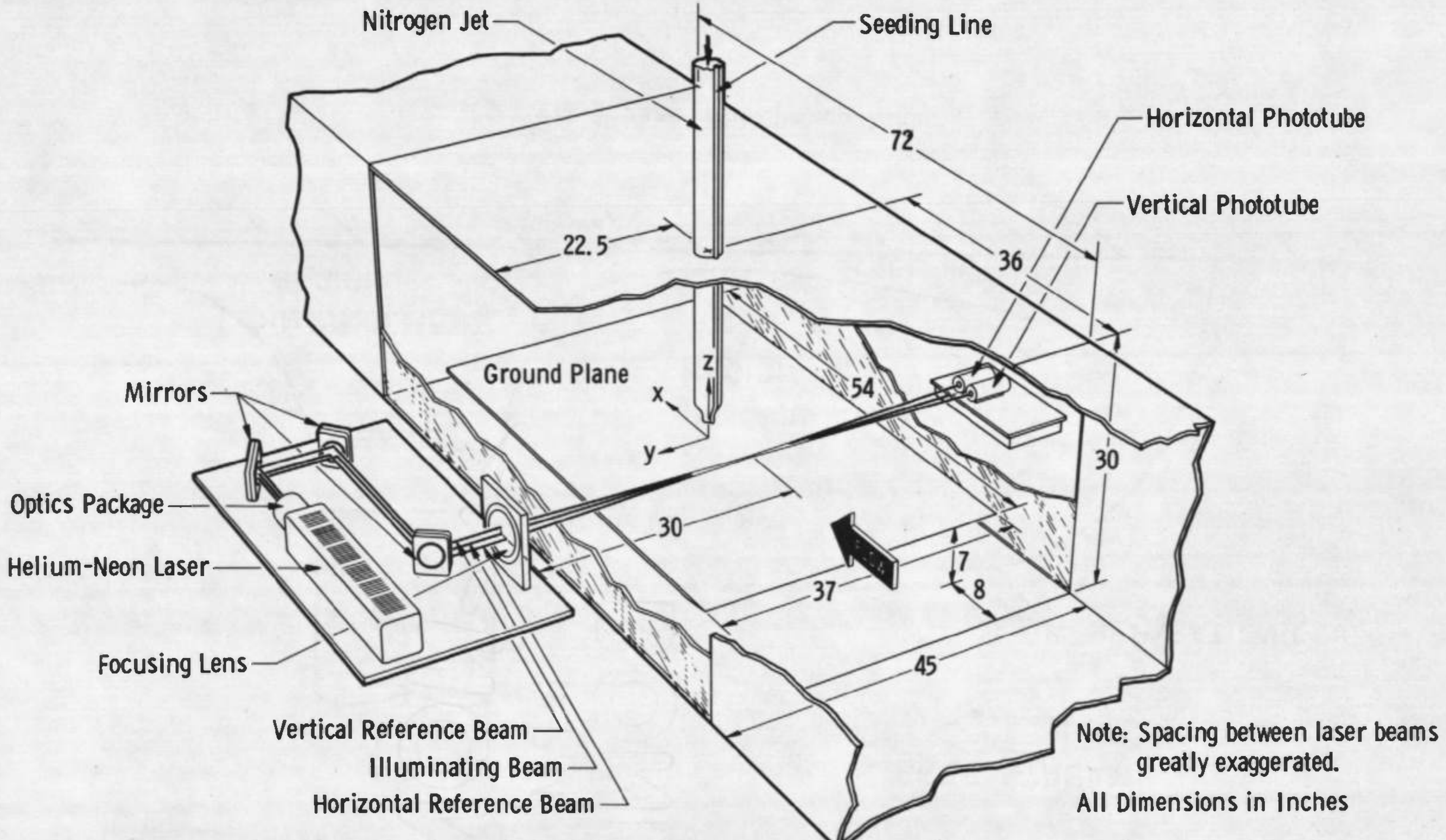


Fig. 2 Location of Test Apparatus in the Low Speed Wind Tunnel

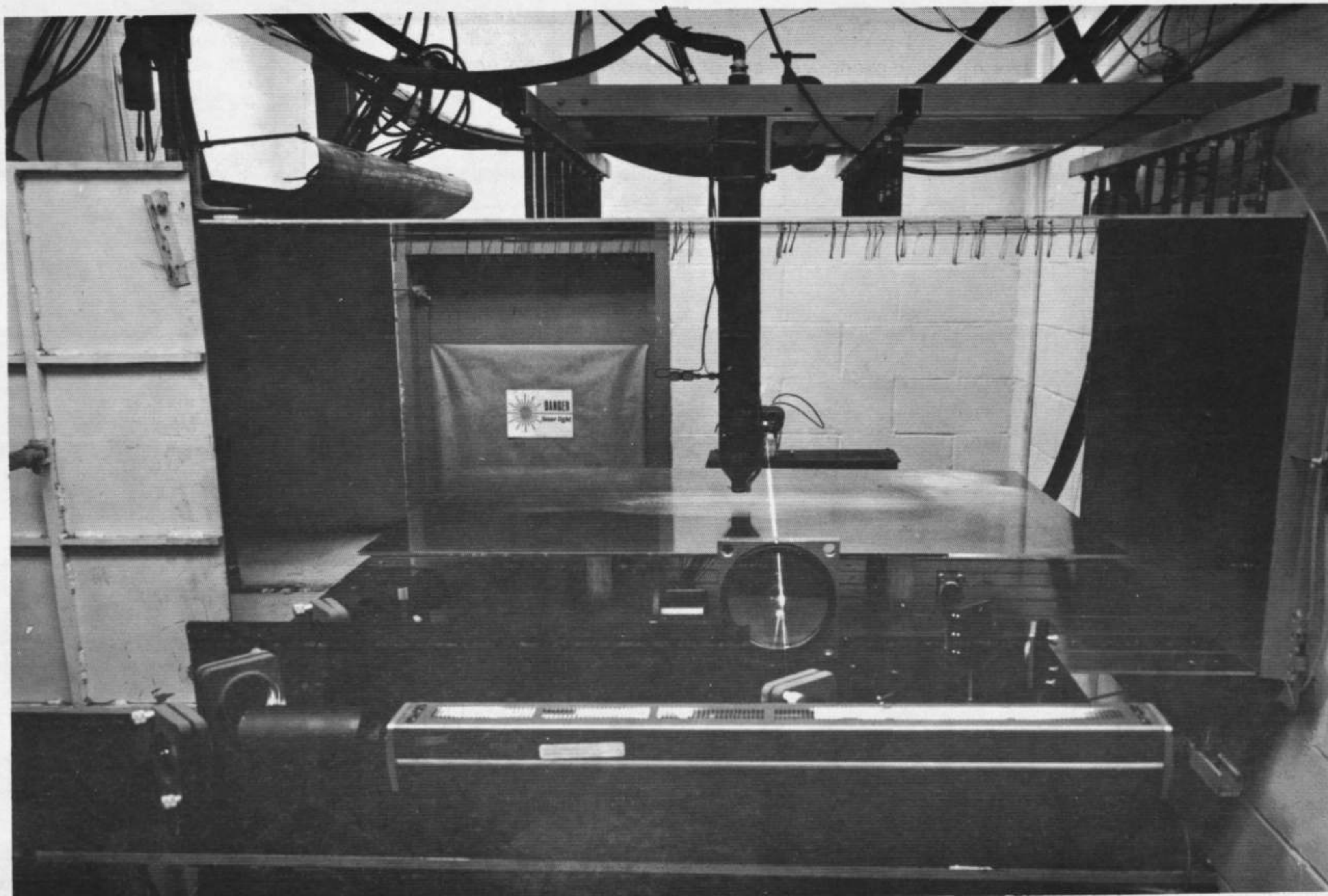


Fig. 3 Test Installation

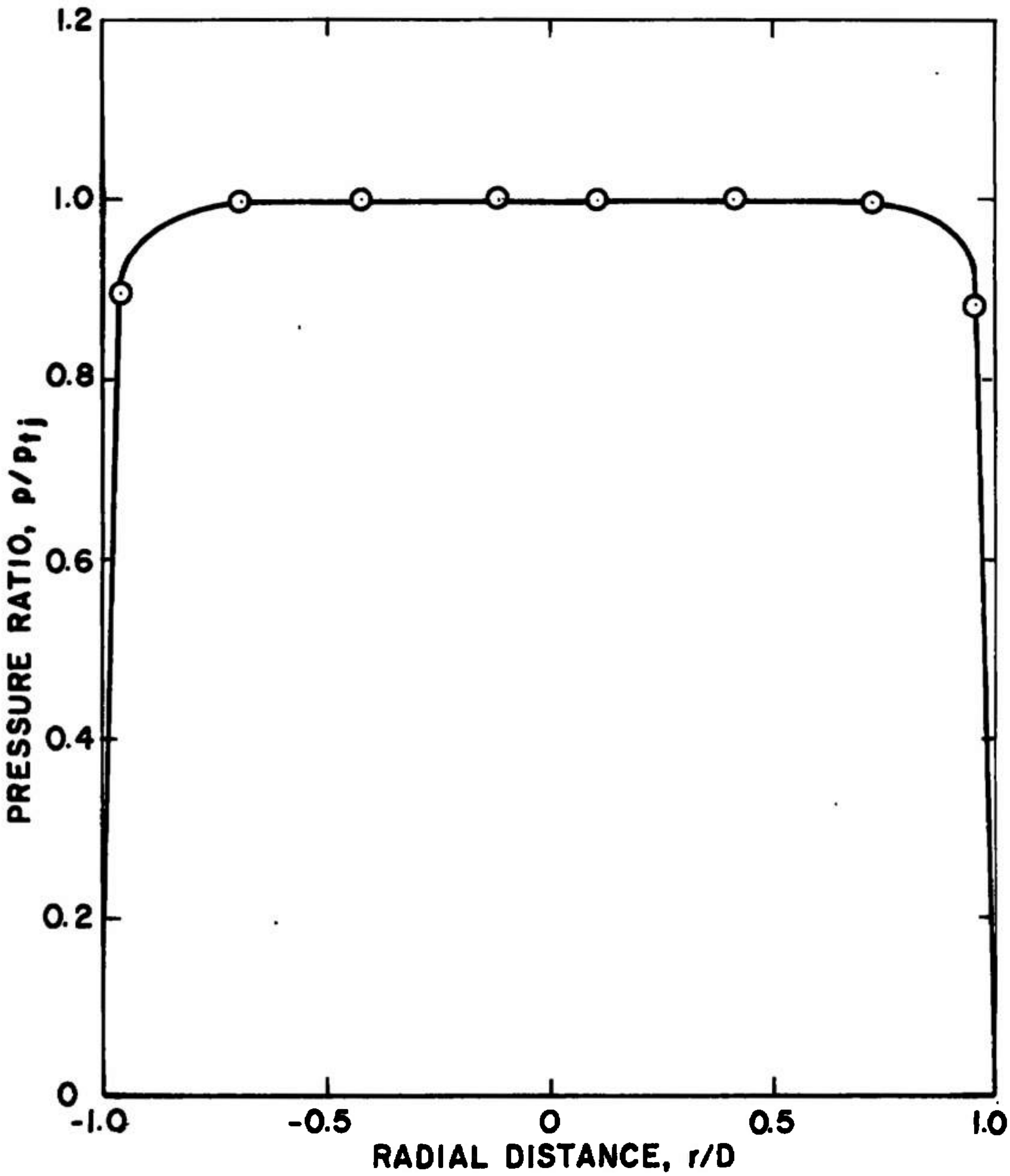
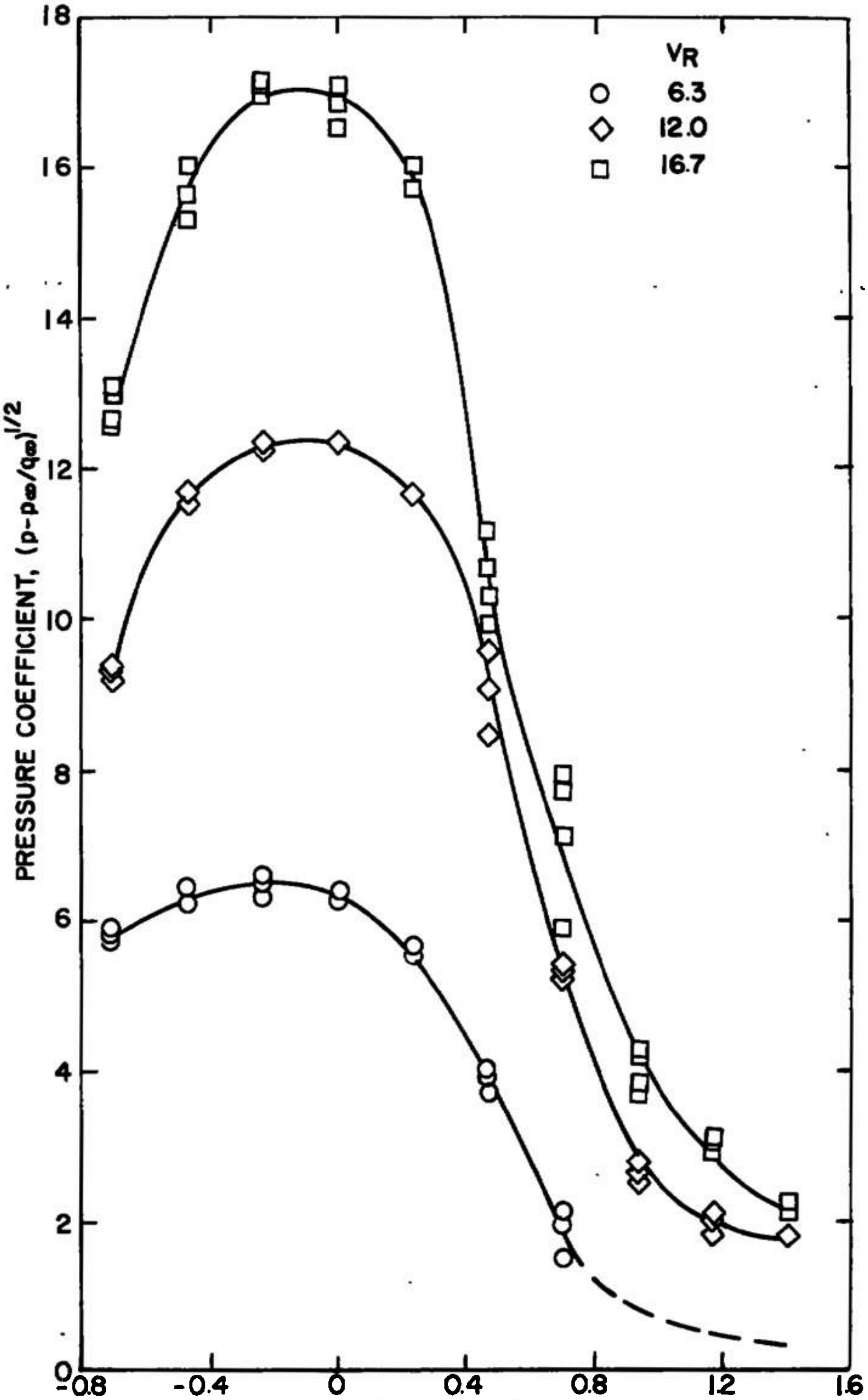
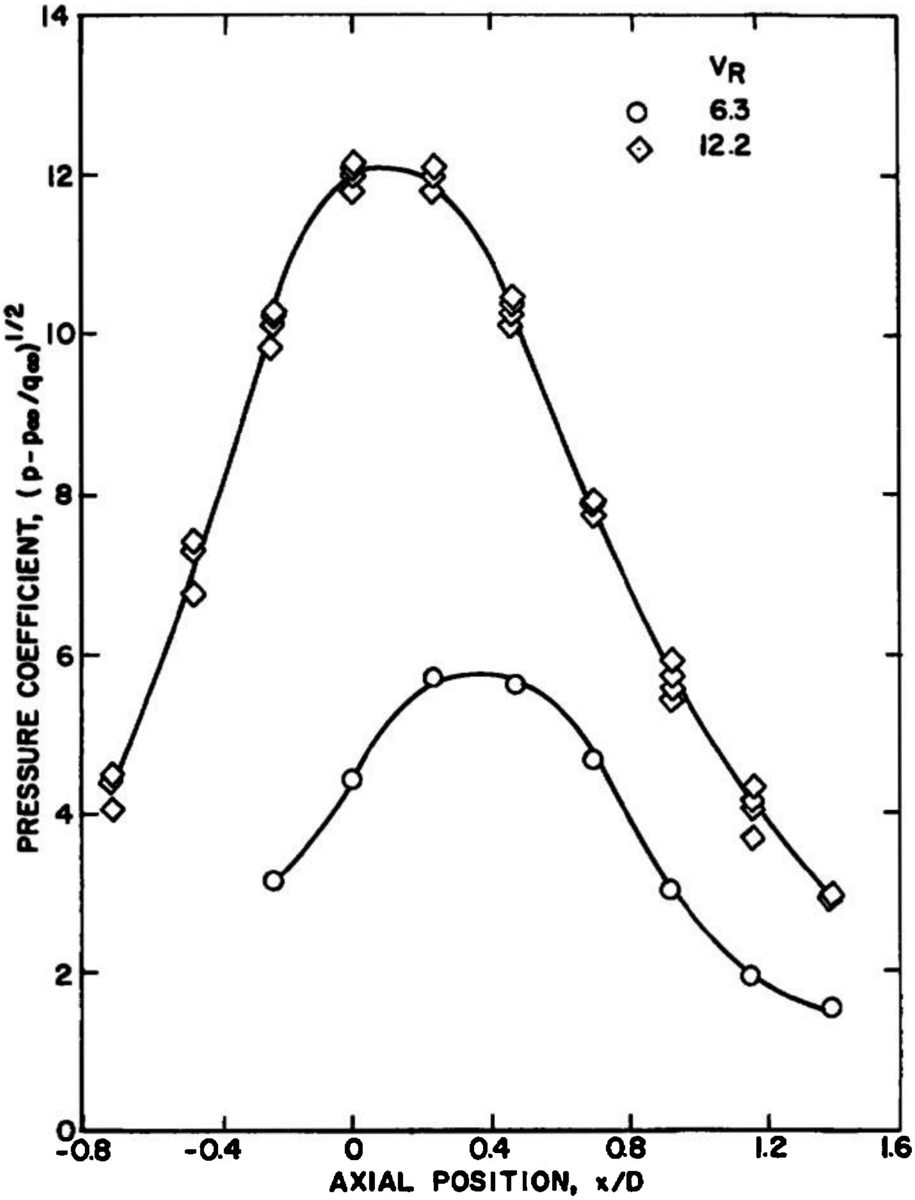


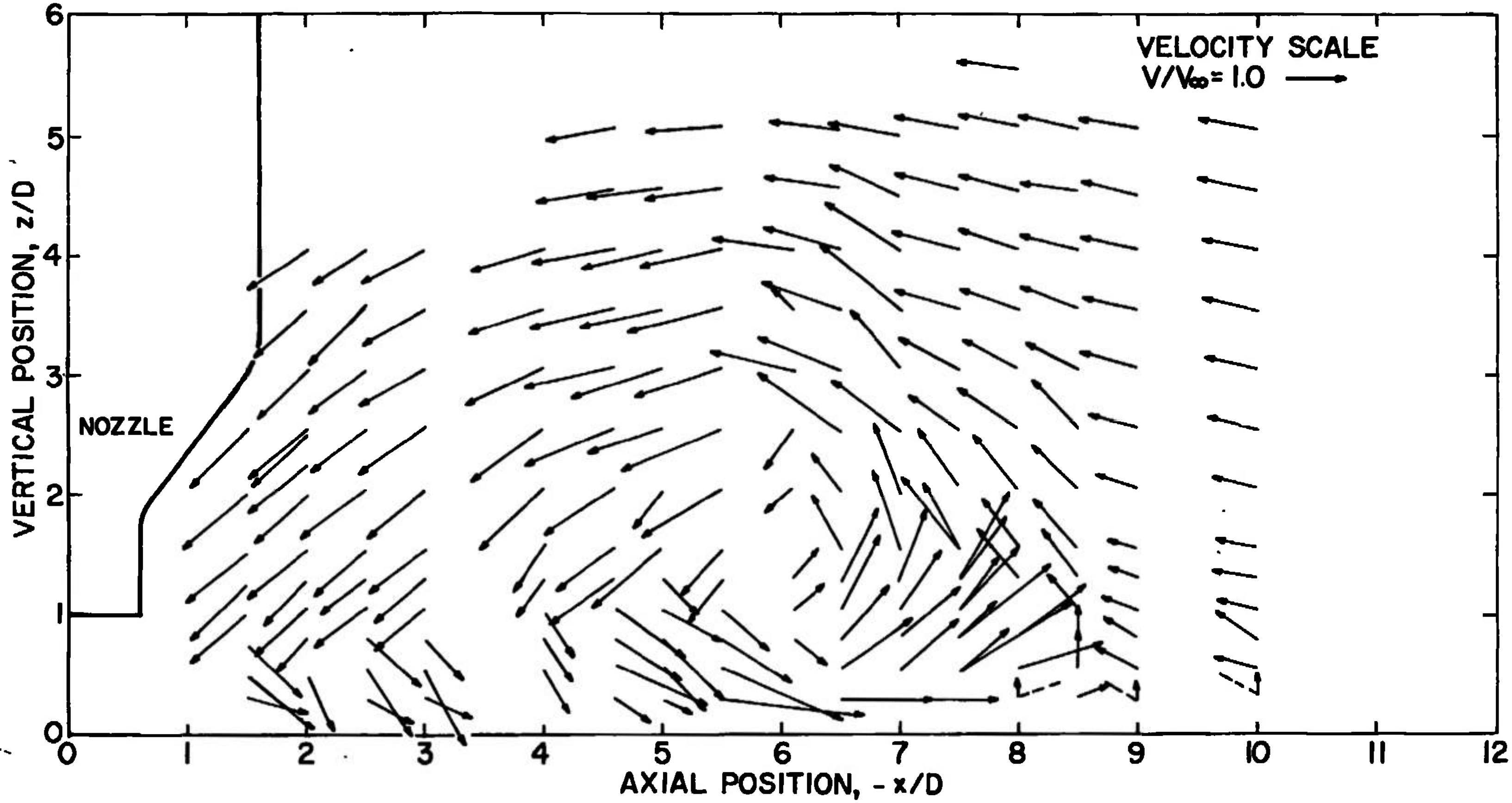
Fig. 4 Nozzle Exit Pressure Distribution



a. h/D = 1
Fig. 5 Impingement Region

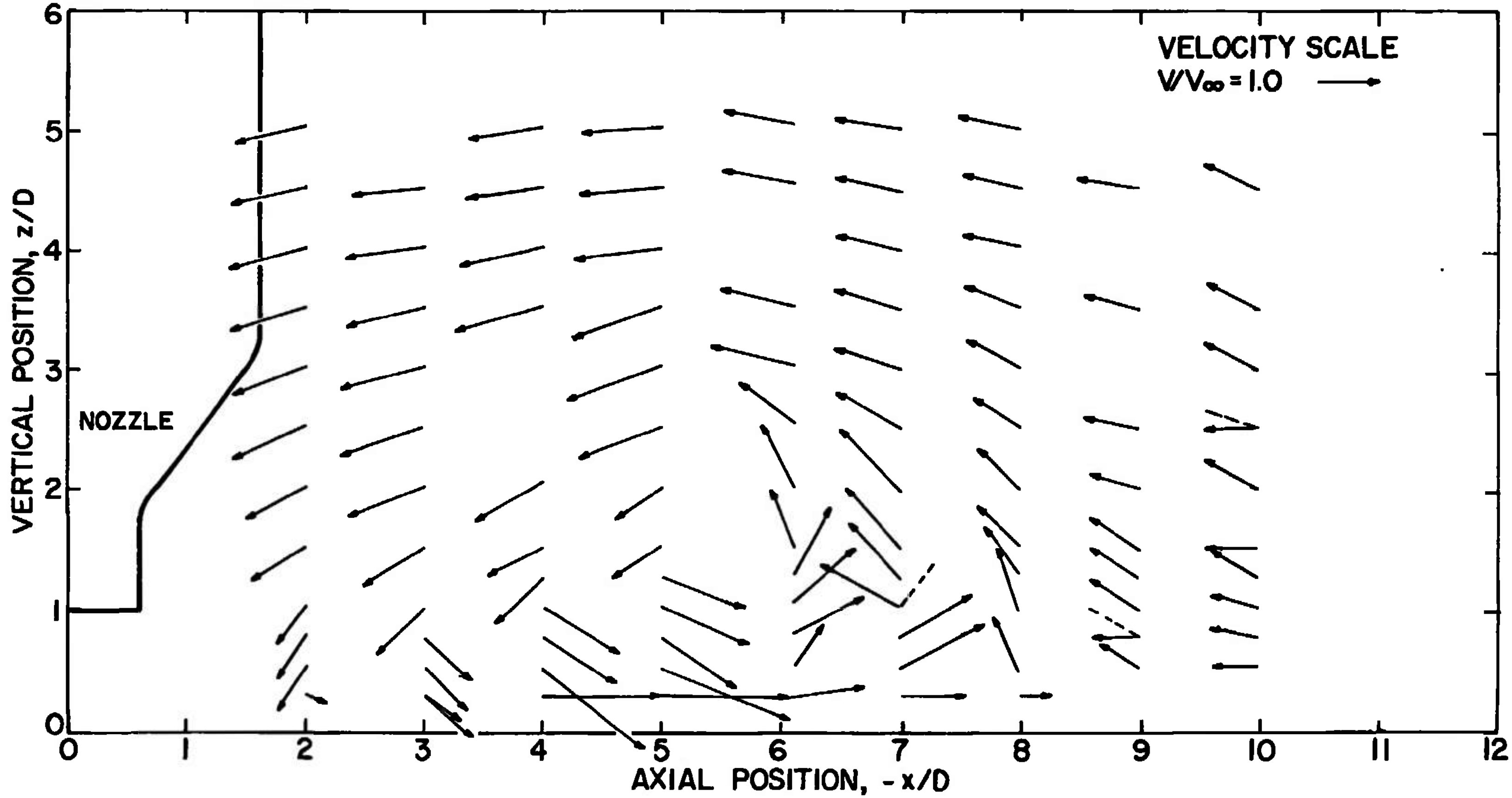


b. h/D = 4
Fig. 5 Concluded

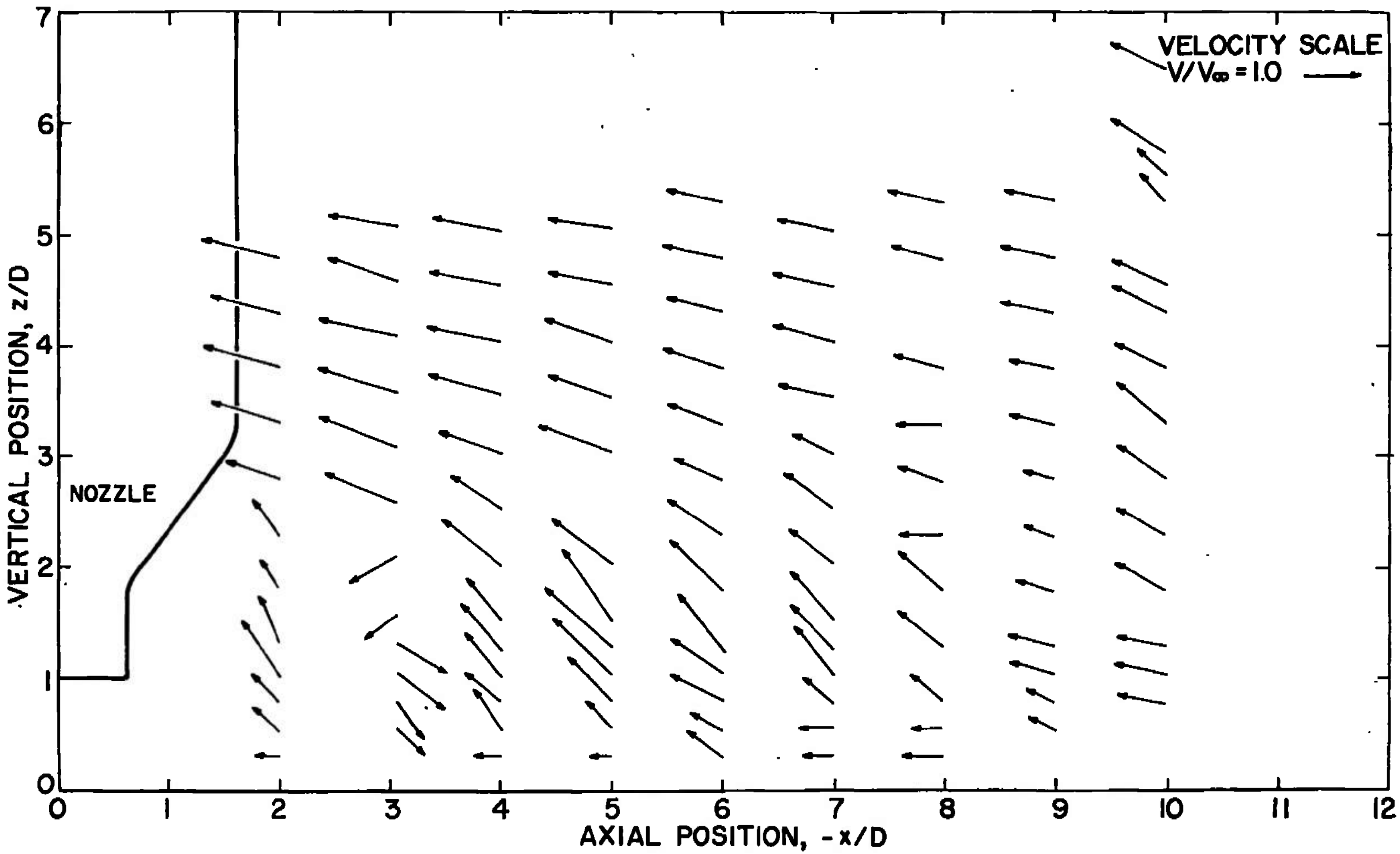


a. y/D = 0

Fig. 6 Velocity Field, V_R = 16.7, h/D = 1



b. y/D = 4
Fig. 6 Continued



c. y/D = 8
Fig. 6 Concluded

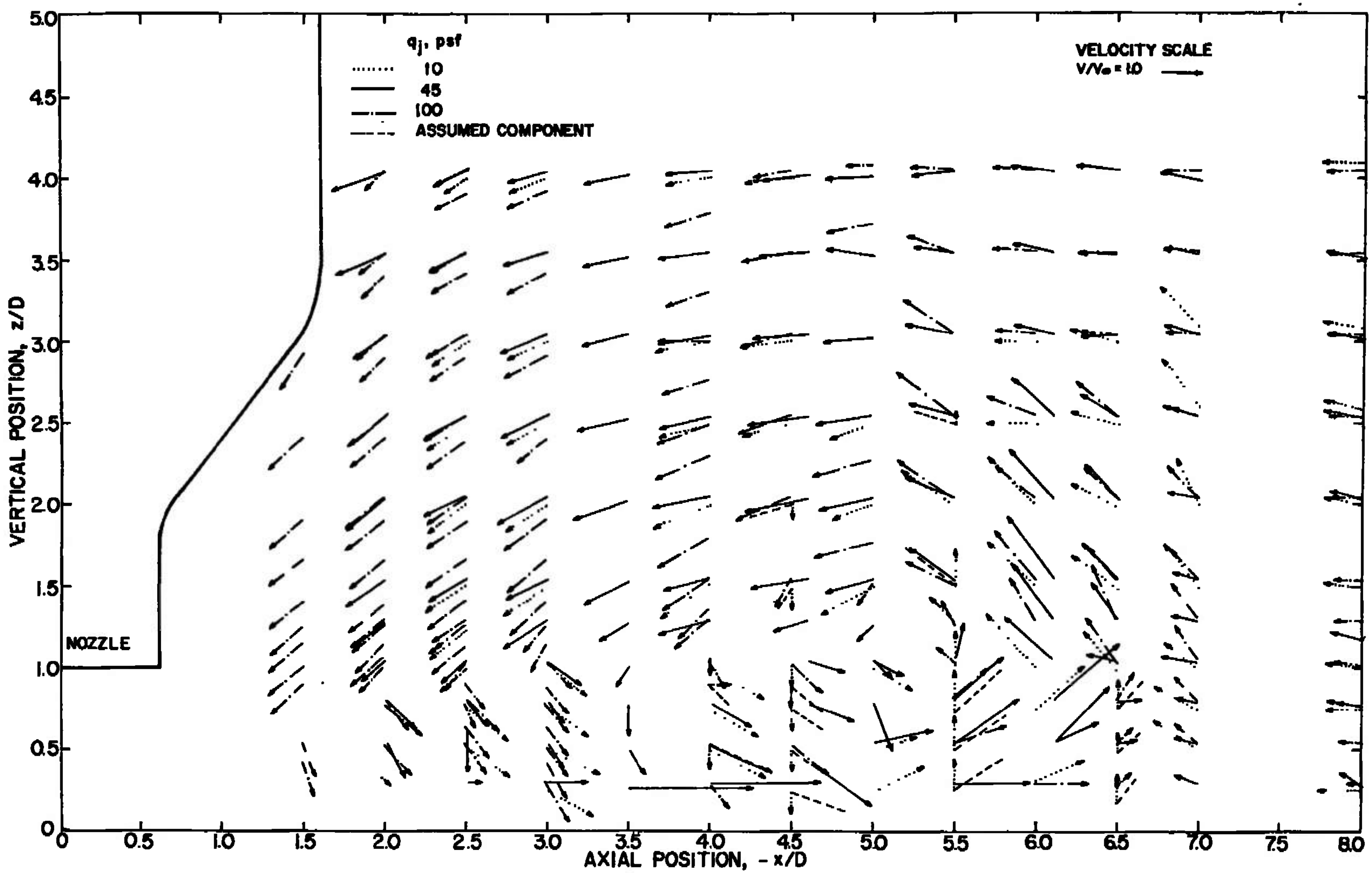


Fig. 7 Velocity Field, V_R = 12, h/D = 1, y/D = 0

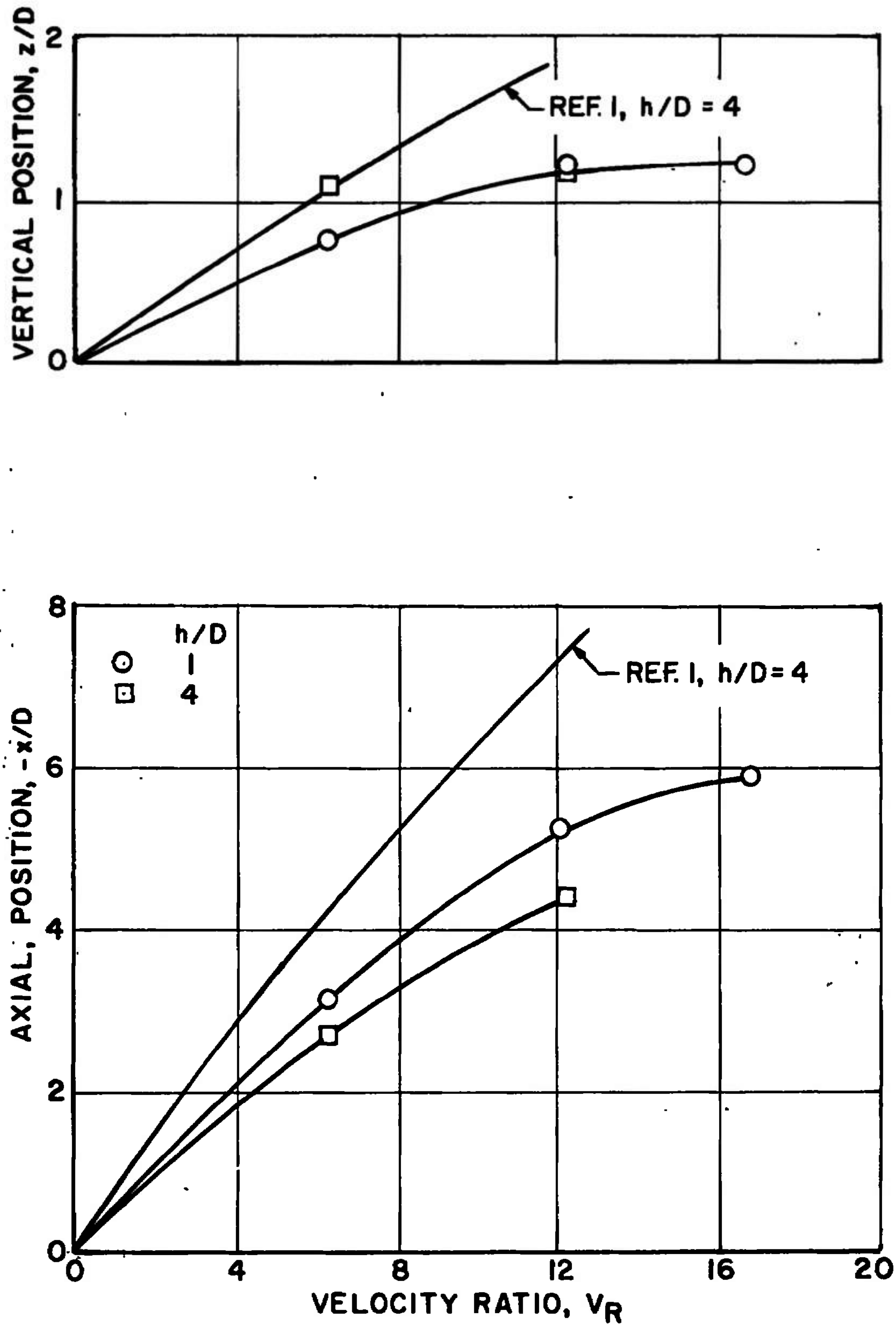


Fig. 8 Location of Apparent Recirculation Center

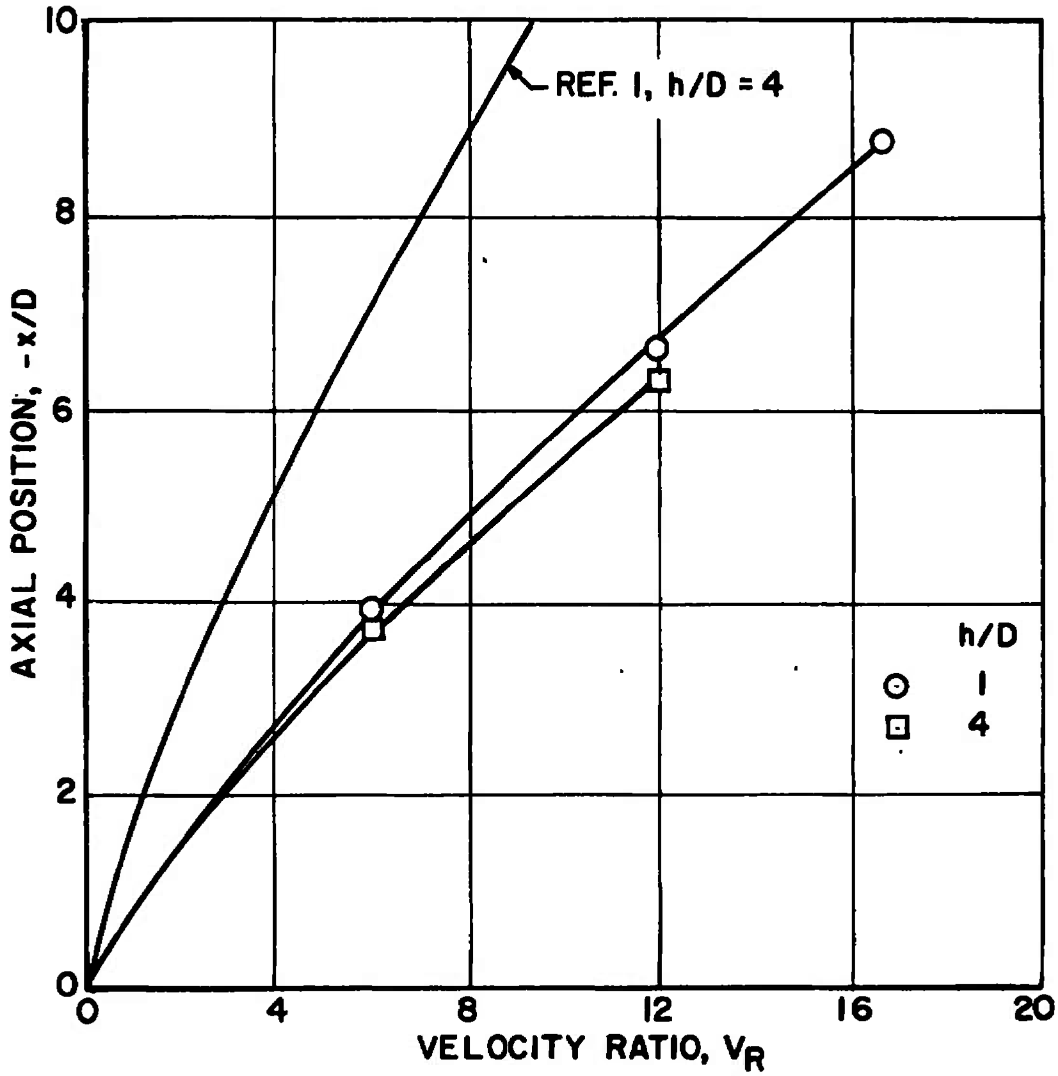


Fig. 9 Location of Free-Stream Separation Point, y = 0, z = 0

TABLE I
SUMMARY OF TEST CONDITIONS

h/D	q_j	V_R	y/D	x/D
1	10	6.3	0, 2, 4, 6, 8	1.5 to 5
1	10	12.6	0, 4, 8, 10, 12	1.5 to 8
1	45	12.0	0, 4, 8	2 to 8
1	45	16.7	0, 4, 8	1.5 to 10
1	100	12.0	0, 4, 8	1.5 to 8
4	10	6.3	0, 4	1 to 4
4	10	12.2	0, 4, 8	1 to 12

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13. ABSTRACT

A wind tunnel investigation was conducted in the Low Speed Wind Tunnel (V/STOL) to determine the velocities in the recirculation region of the flow field produced by the interaction of a jet impinging on a ground plane with crossflow. Axial and vertical velocity component measurements were obtained with a forward-scattering laser Doppler velocimeter. Test results provide two-component velocity fields and indicate that the jet-to-free-stream velocity ratio is much more important in determining the flow field than the magnitude of the individual velocities.

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velocity measurement						
pressure distribution						
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wind tunnels						

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